Growing Food for Space and Earth:

NASA's Contributions to Vertical Agriculture

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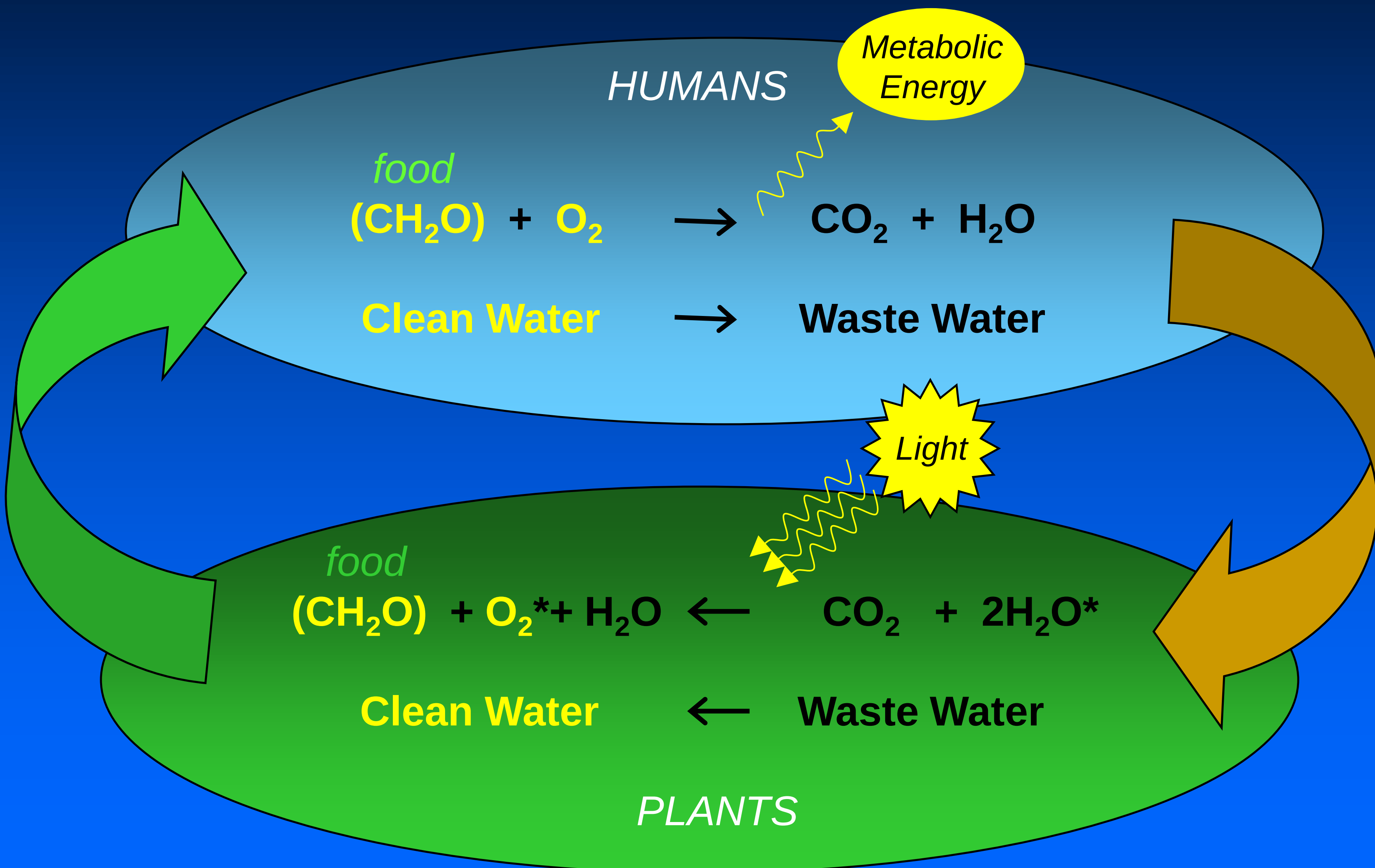
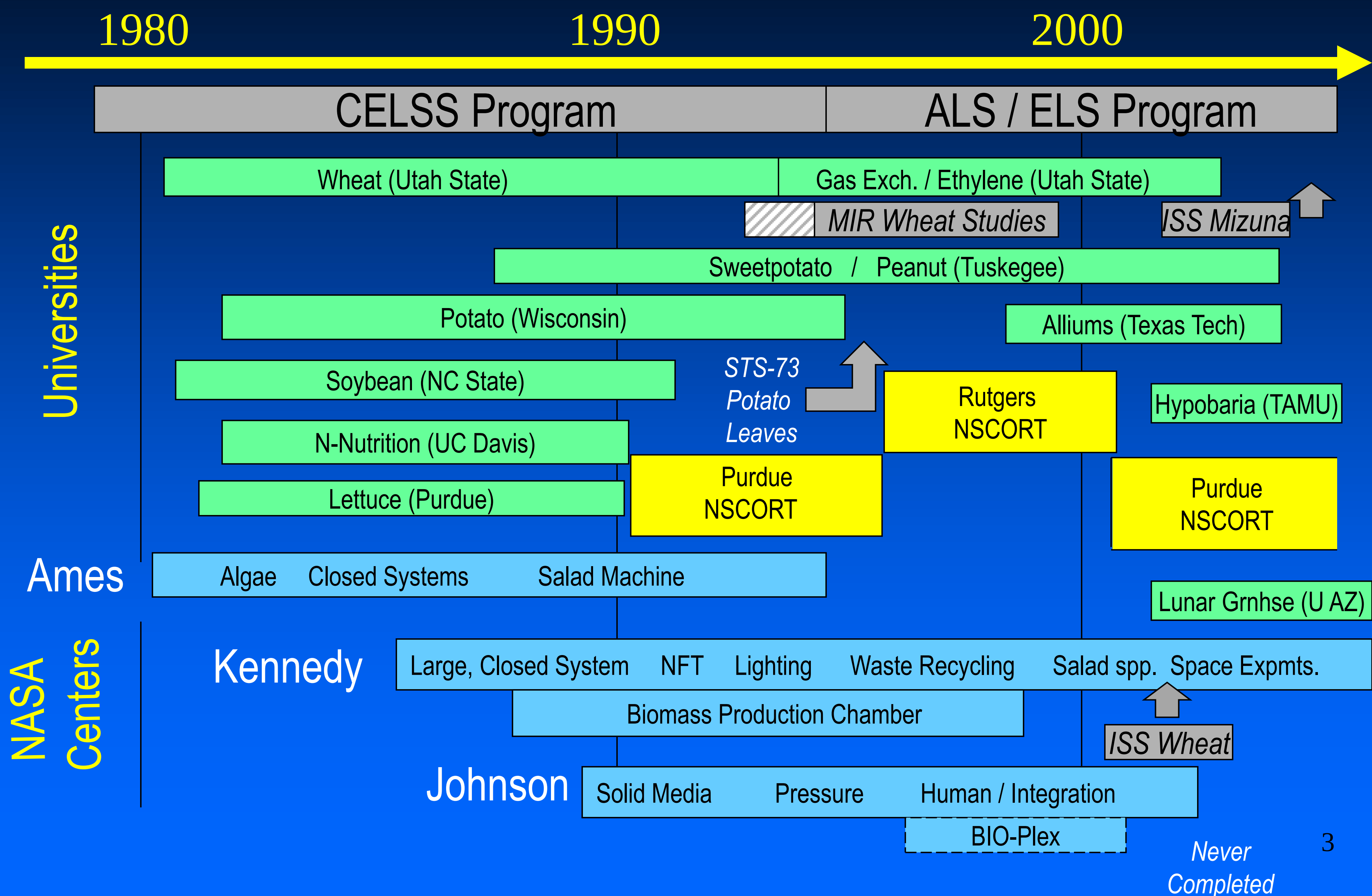
Plants for “Bioregenerative” Life Support



NASA's Bioregenerative Life Support Testing



Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
- High harvest index (edible / total biomass)
- Horticultural considerations
  - planting, watering, harvesting, pollination, propagation
- Environmental considerations
  - lighting, temperature, mineral nutrition, CO_2
- Processing requirements
- Dwarf or low growing types

Recirculating Hydroponics with Crops

Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting

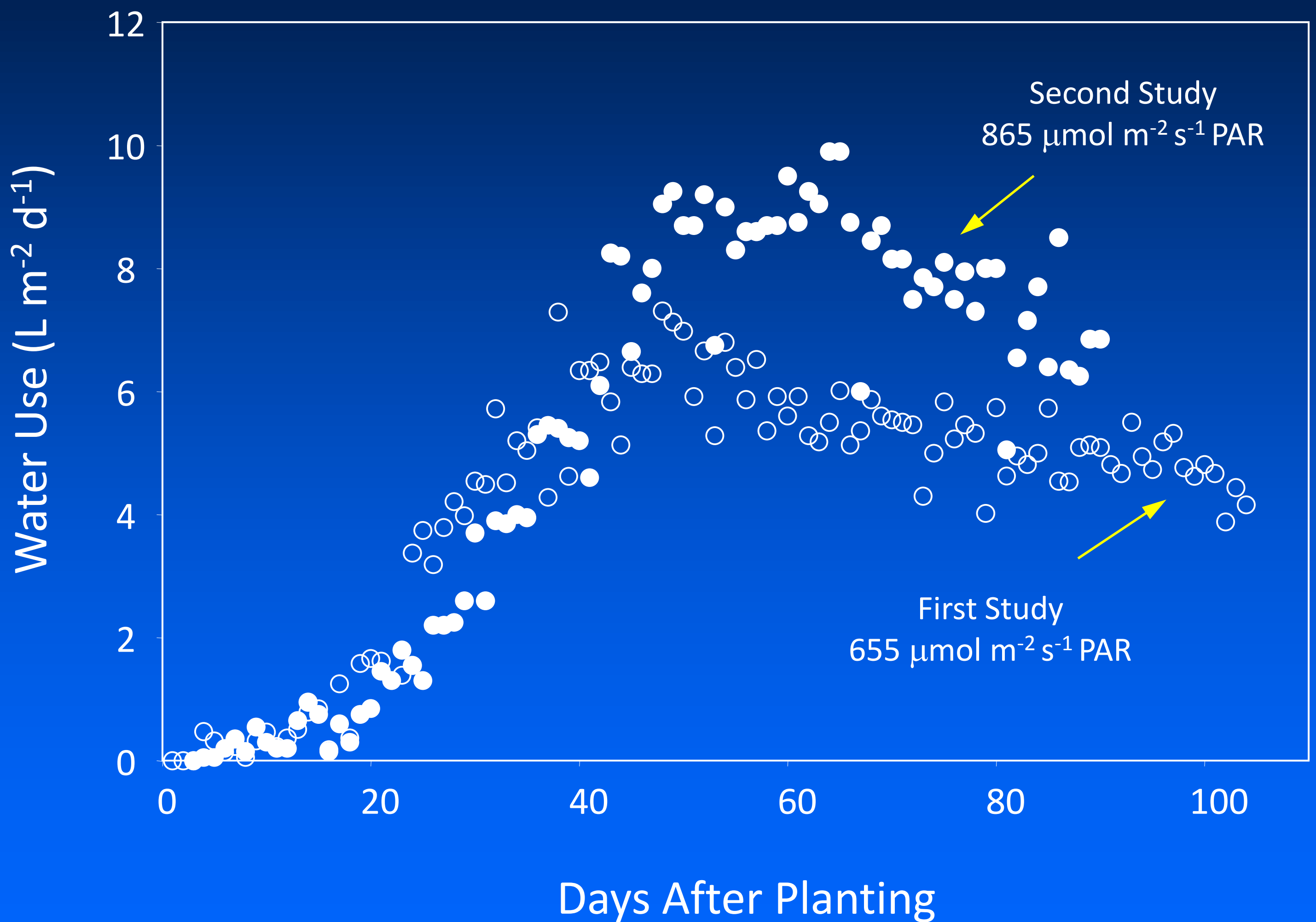
Wheeler et al., 1999. Acta Hort.

Root Zone Crops in Nutrient Film Technique (NFT)

Wheeler et al., 1990. Amer. Potato J. 67:177-187; Mackowiak et al. 1998. HortScience 33:650-651

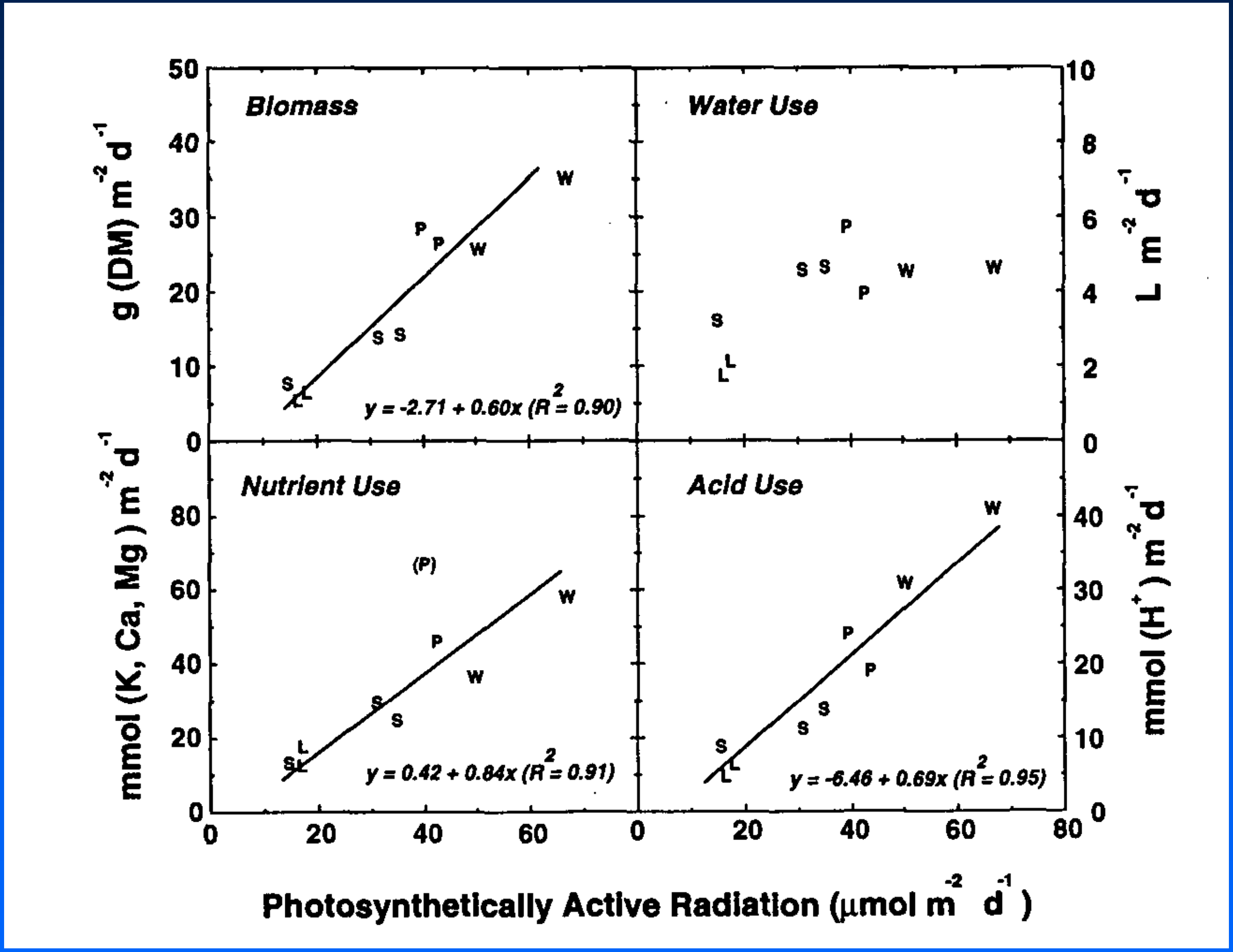
Fig. 7

Evapotranspiration from Plant Stand (potato)



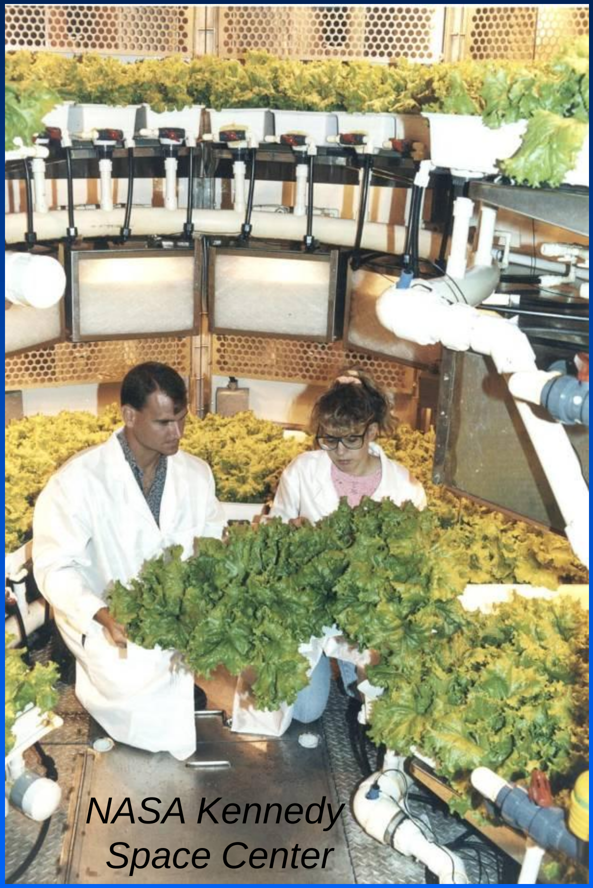
Wheeler. 2006. Potato Research 49:67-90.

Water, Nutrient, and pH Control



Wheeler et al. 1999. Acta Hort.

High Yields from High Light and CO_2 Enrichment



Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models

Bubgee, B.G. and F.B. Salisbury. 1988. Plant Physiol. 88:869-878.
Wheeler, R.M., T.W. Tibbitts, A.H. Fitzpatrick. 1991. Crop Science 31:1209-1213.

Potential Energy Conversion to Biomass

From Loomis and Williams. 1963. Crop Science 3:67-72

Assuming a maximum 12% conversion efficiency from PAR to biomass[1]

1.6 g dry mass / mol PAR

[1] Radmer and Kok. 1977. BioScience. Actual instantaneous conversion efficiencies of ~10% reported from some controlled environment studies ; e.g., Wheeler et al., 1993. Crop Sci.; Gerbaud et al., 1998. Physiol. Plant.

Some Upper Limits to Energy Conversion and Productivity

Field Crops Observations[1]

Crop	Productivity	Photosynthetic Energy Conversion Efficiency [2]
	(g DM m^{-2} d^{-1})	(%)
Tall Fescue	43	7.0 (UK)
Maize	40	6.8 (US)
Sudan Grass	52	6.0 (US)

CEA NASA Studies

Crop	Productivity	Radiation Use Efficiency
	(g DM m^{-2} d^{-1})	(g DM mol^{-1} PAR)
Wheat	61	1.44 Utah State[3]
	130	0.67 Utah State[4]
Potato (12⇨24 h photoper.)	45	0.97 Univ. Wisc.[5]
(12 h photoper. only)	38	1.15 Univ. Wisc.[5]

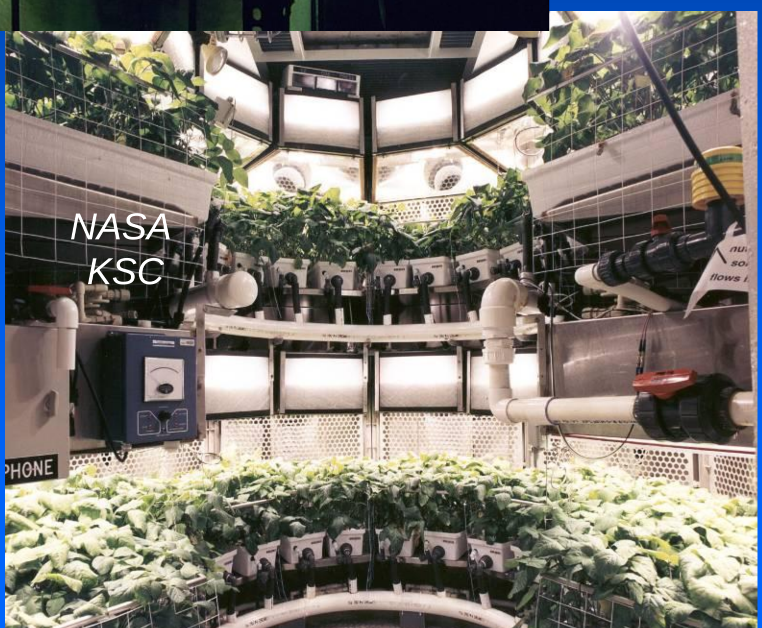
[1] *D.O. Hall. 1976. FEBS Letters*
[2] *Original data based on total solar irradiance; table data reflect efficiency based on PAR (400-700 nm)*
[3] *Monje and Bugbee. 1998. Plant Cell Environ (estimated)*
[4] *Bugbee and Salisbury. 1988. Plant Physiol.*
[5] *From Wheeler, 2006. Potato Res. (assumes transplanting to increase PAR absorption).*

Closed Systems Issues


NASA Ames Research Center

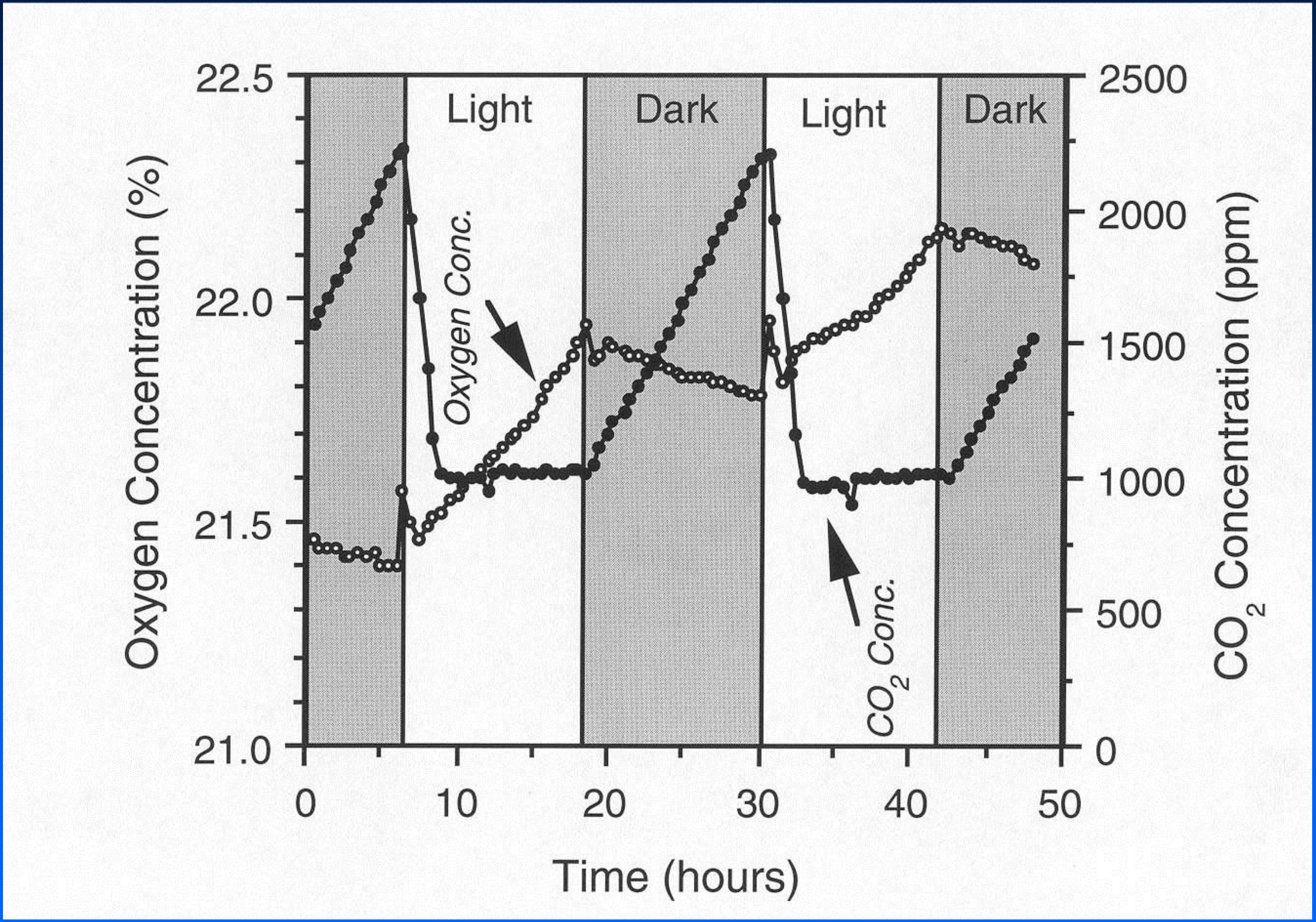

Purdue Univ.


NASA Johnson Space Center


NASA KSC

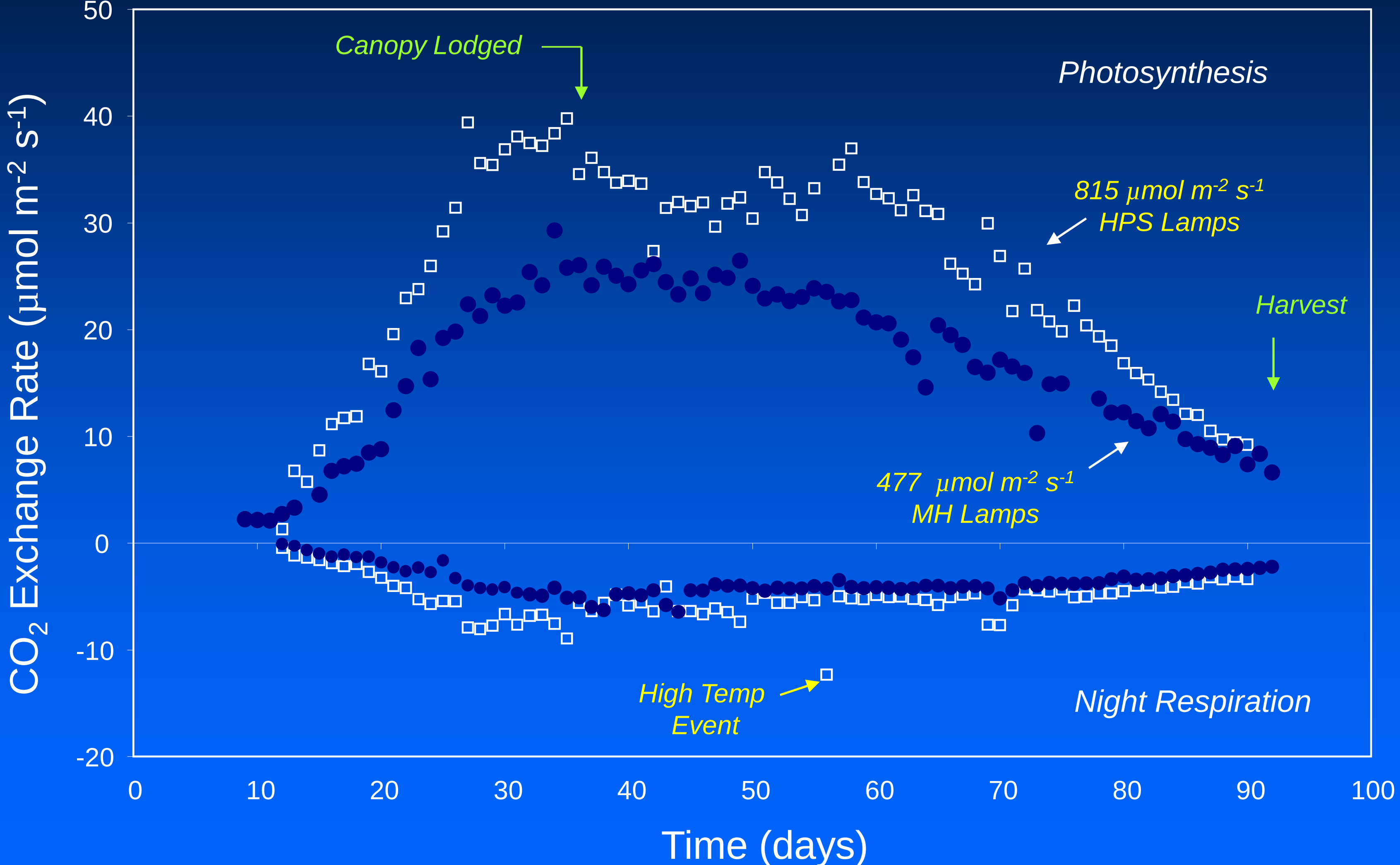
Canopy CO_2 Uptake / O_2 Production

(20 m^2 Soybean Stand)



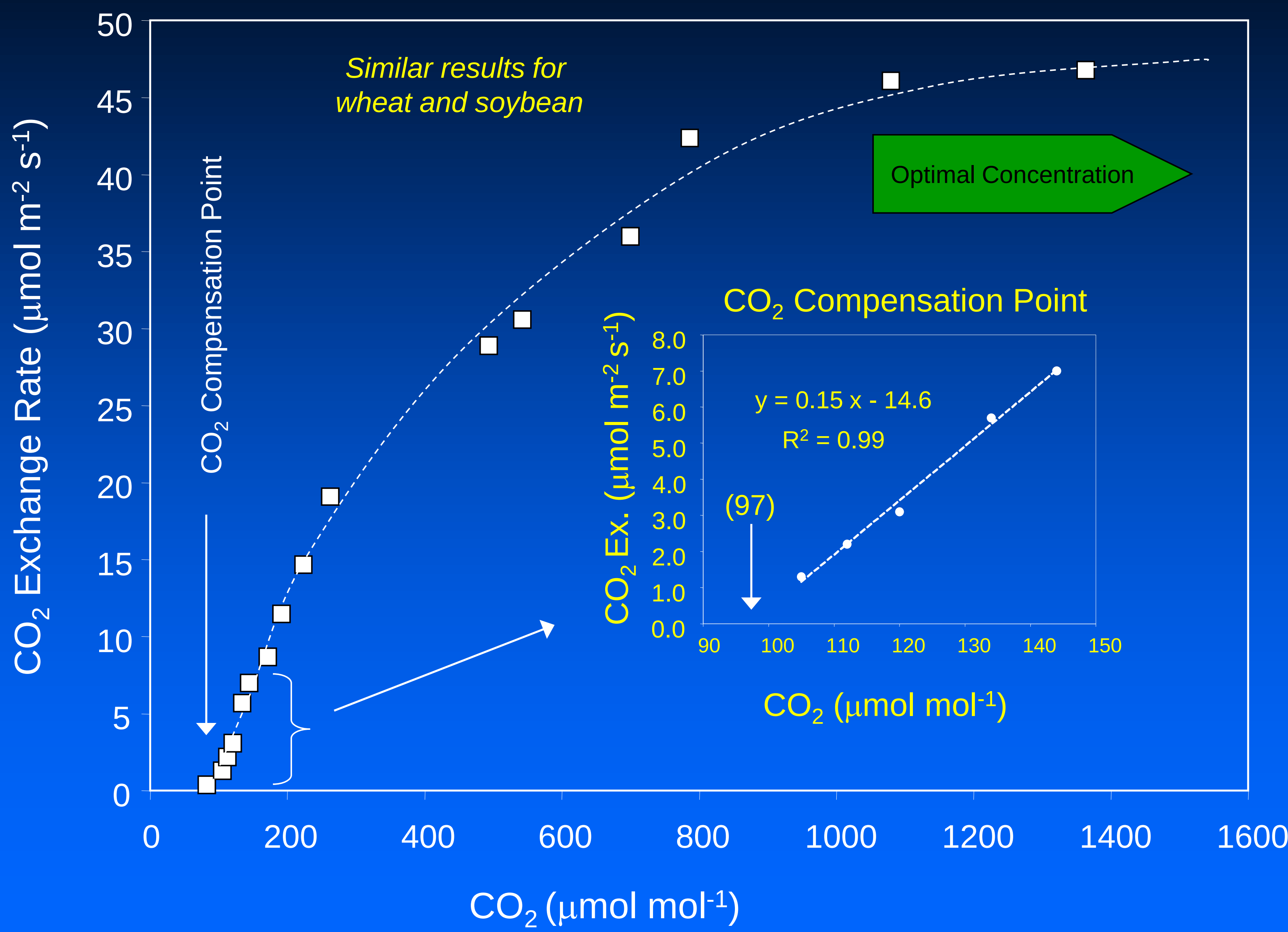
Wheeler. 1996. *In:* H. Suge (*ed*.) Plants in Space Biology.

CO_2 Exchange Rates of Soybean Stands



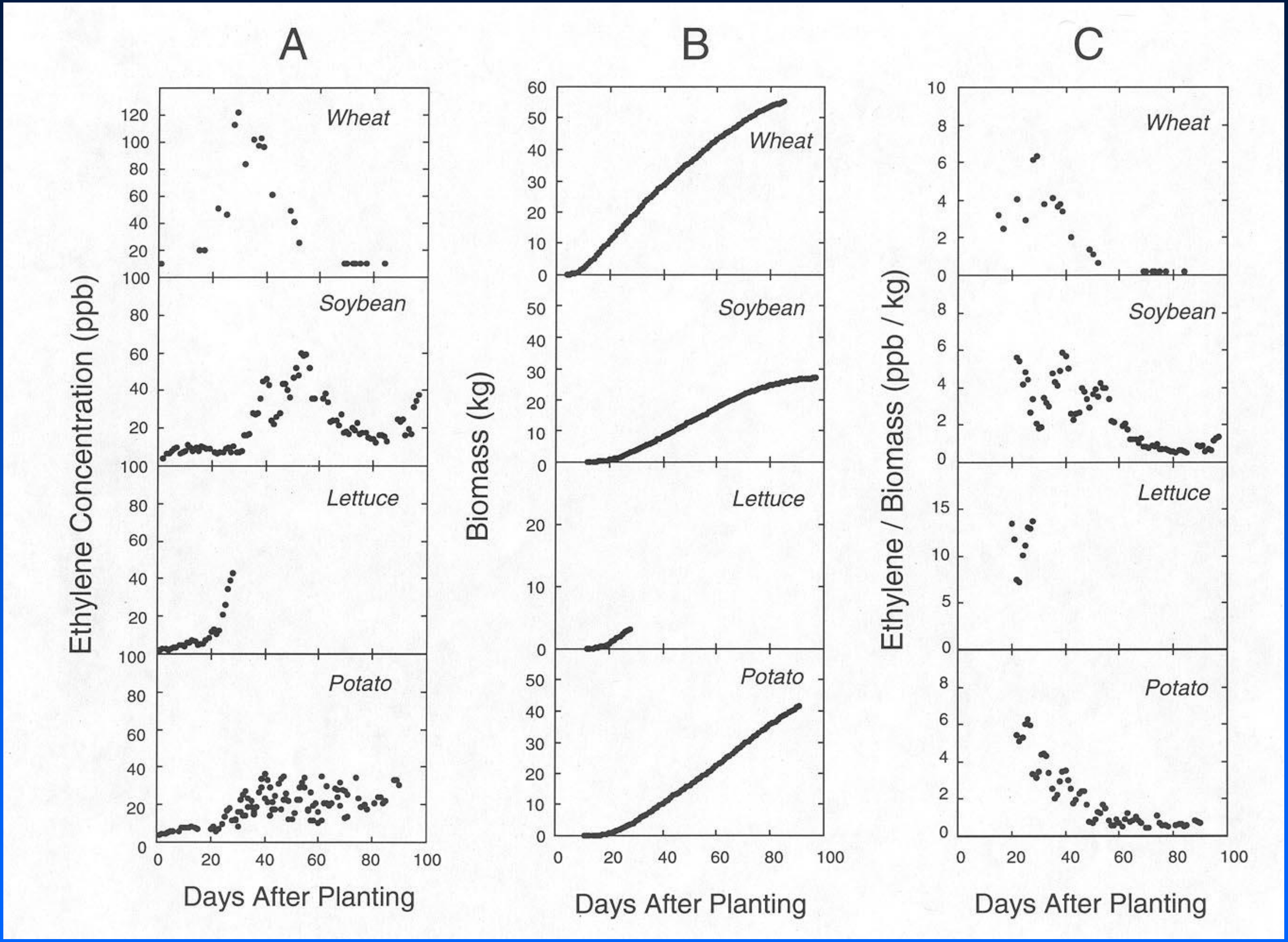
Wheeler et al., 2004. EcoEngineering.

Effect of CO_2 Concentration on Photosynthesis (potato)



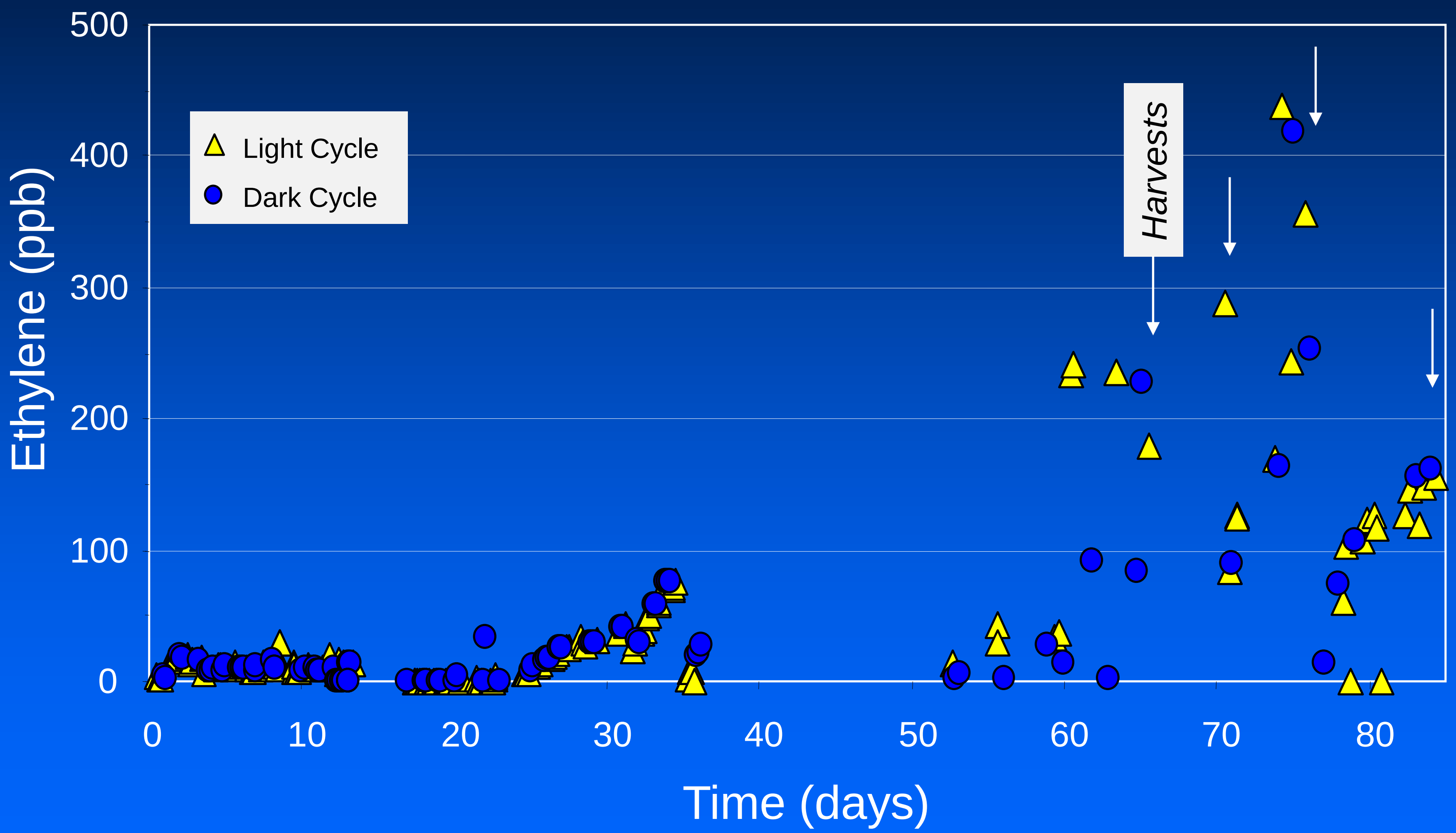
Wheeler. 2006. Potato Research 49:67-90.

Canopy / Stand Ethylene Production



Wheeler et al. 2004. HortScience 39:1541-1545.

Ethylene Production - Tomato cv. Reimann Philipp



Wheeler et al. 2004. HortScience 39:1541-1545.

Ethylene in Closed Systems

Epinastic
Wheat Leaves
at ~120 ppb

Epinastic
Potato Leaves
at ~40 ppb

NASA's Biomass Production Chamber (BPC)

An Attempt at Vertical Agriculture !

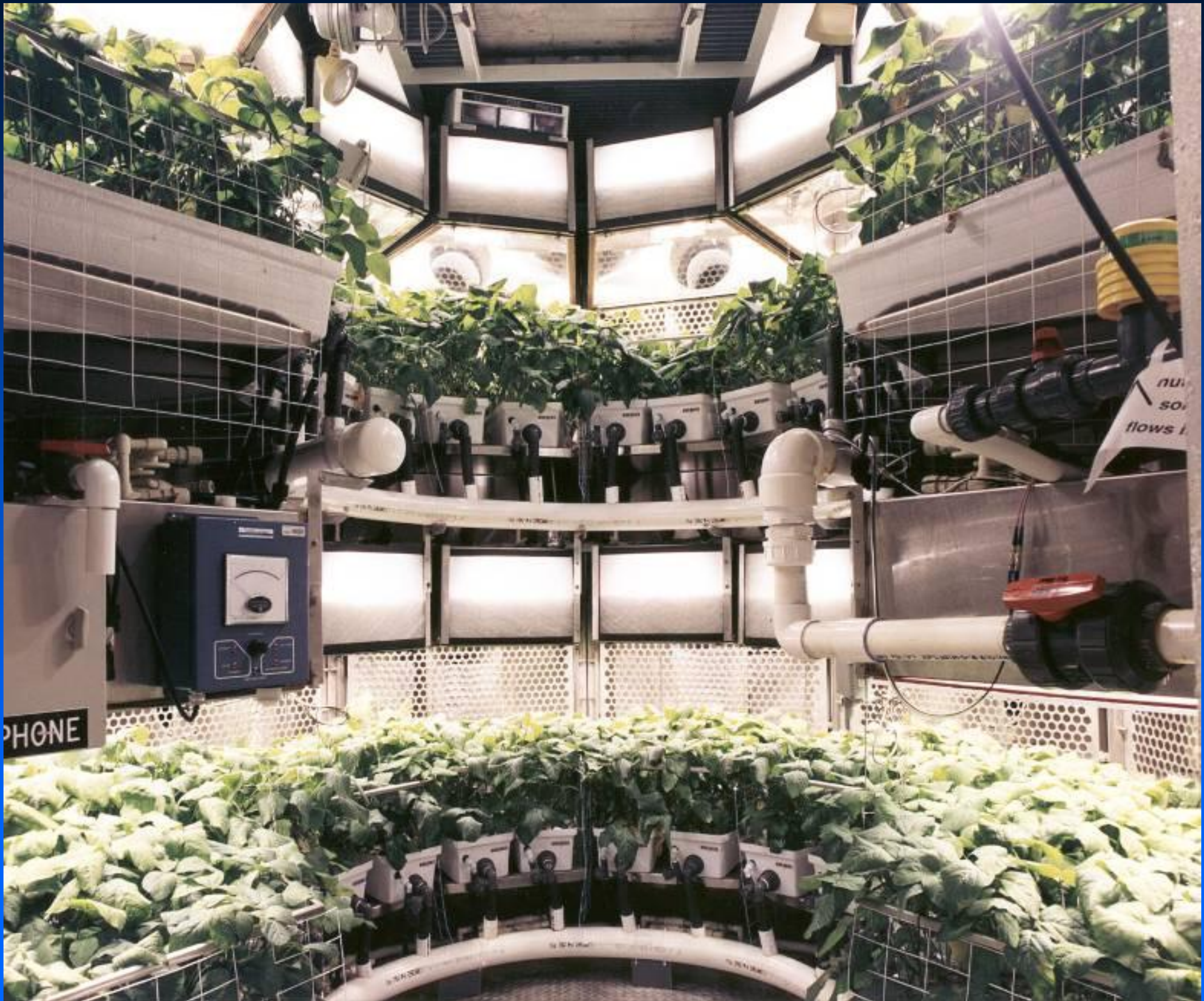
External View - Back

Control Room

Hydroponic System

20 m^2 growing area; 113 m^3 vol.; 96 400-W HPS Lamps;
400 m^3 min^{-1} air circulation; two 52-kW chillers

NASA's Biomass Production Chamber (BPC)

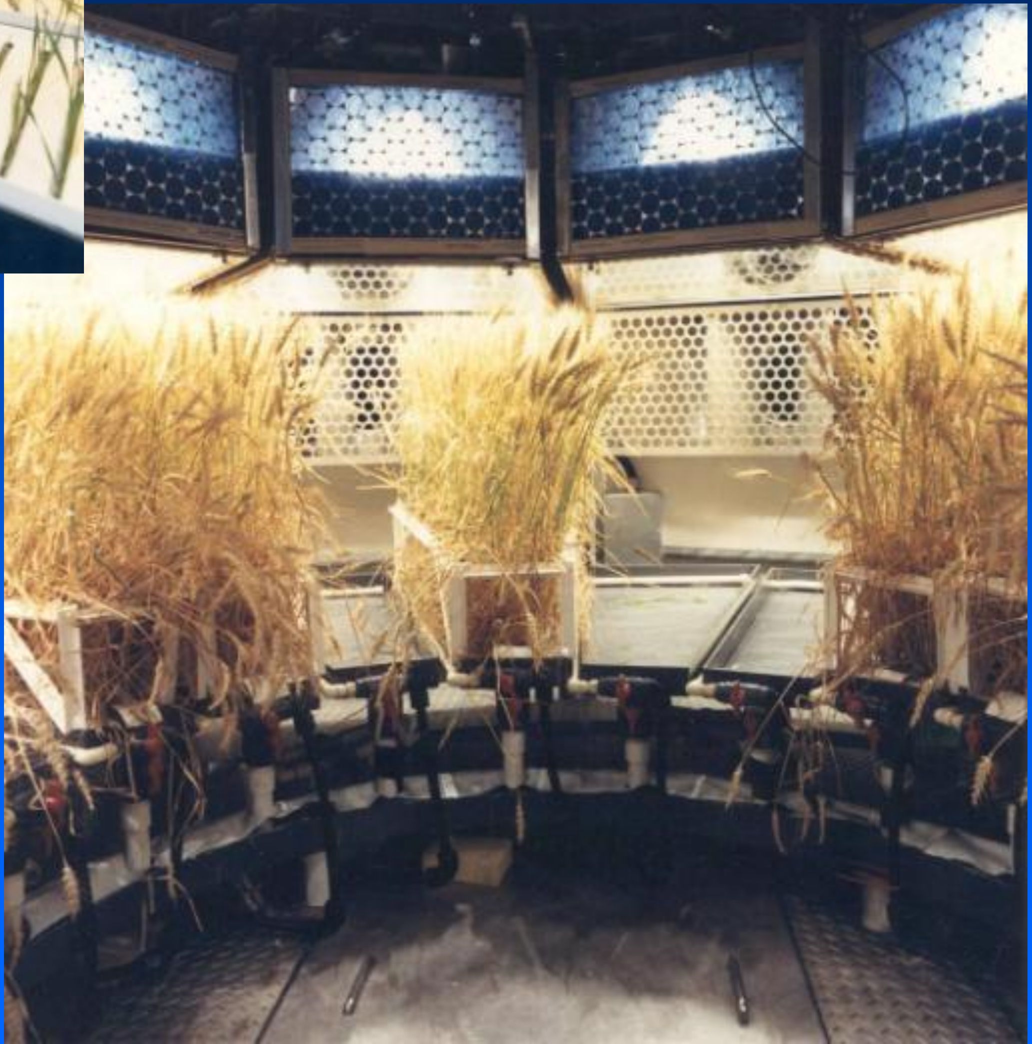


Wheat

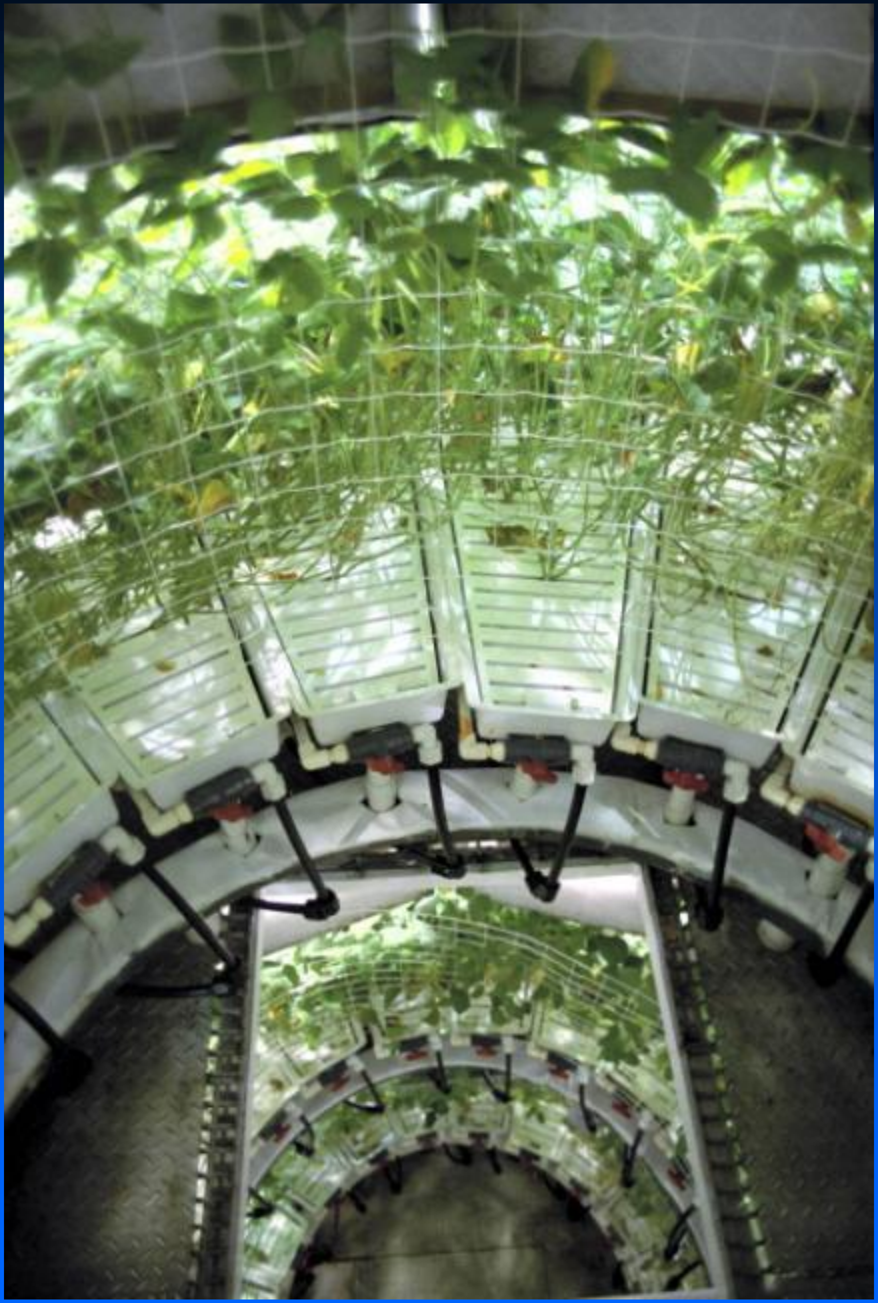
(Triticum aestivum)

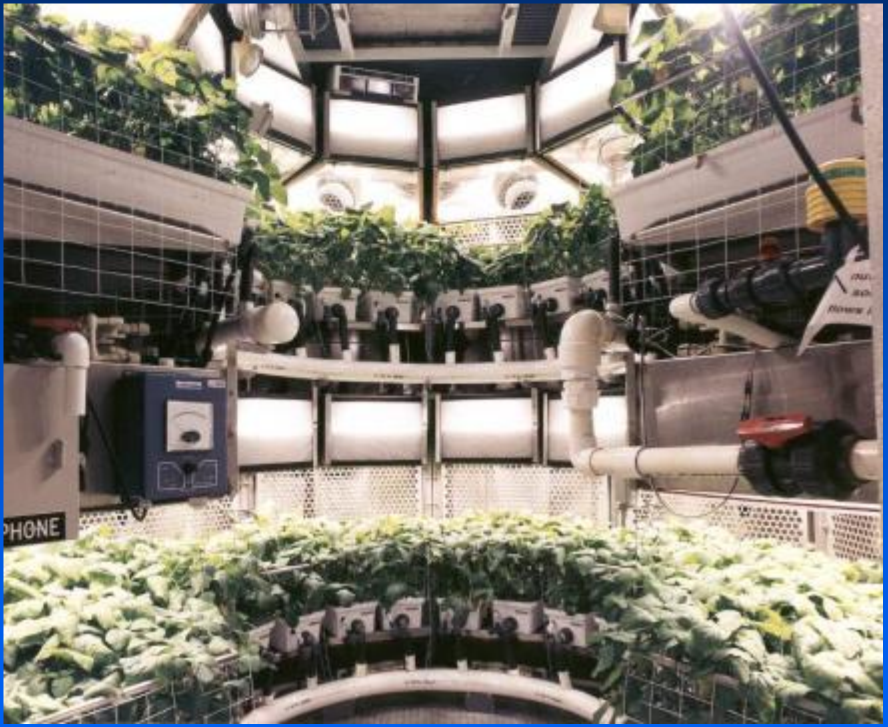
planting

harvest



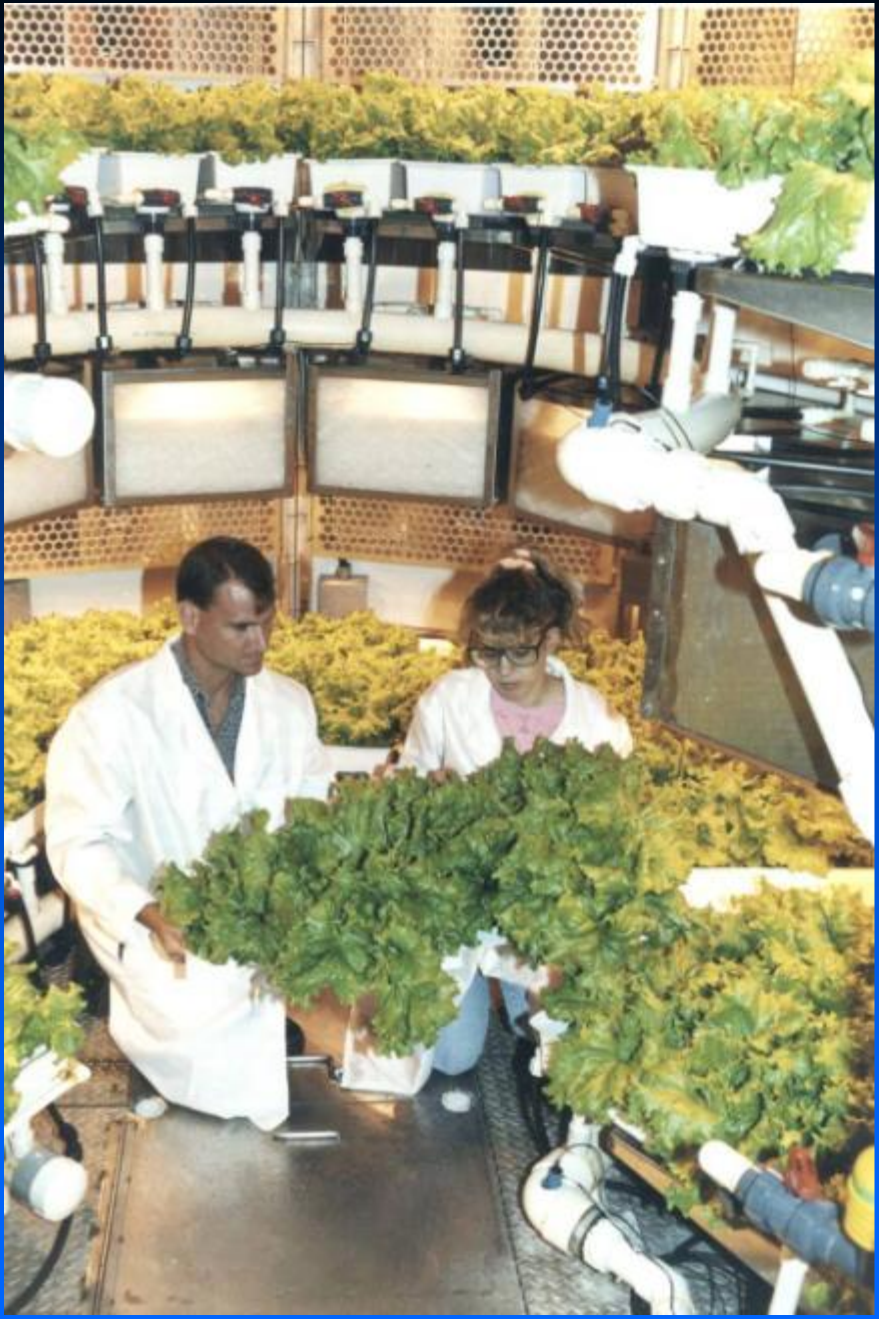
Soybean
(Glycine max)





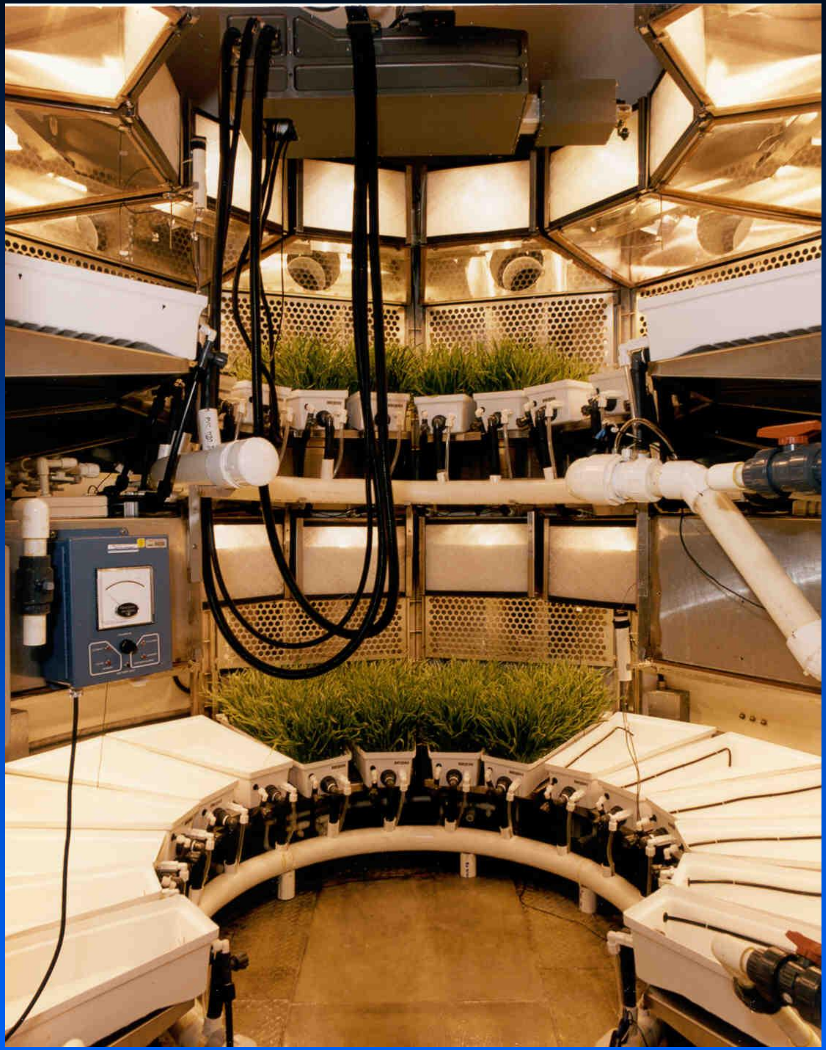
Lettuce

(Lactuca sativa)



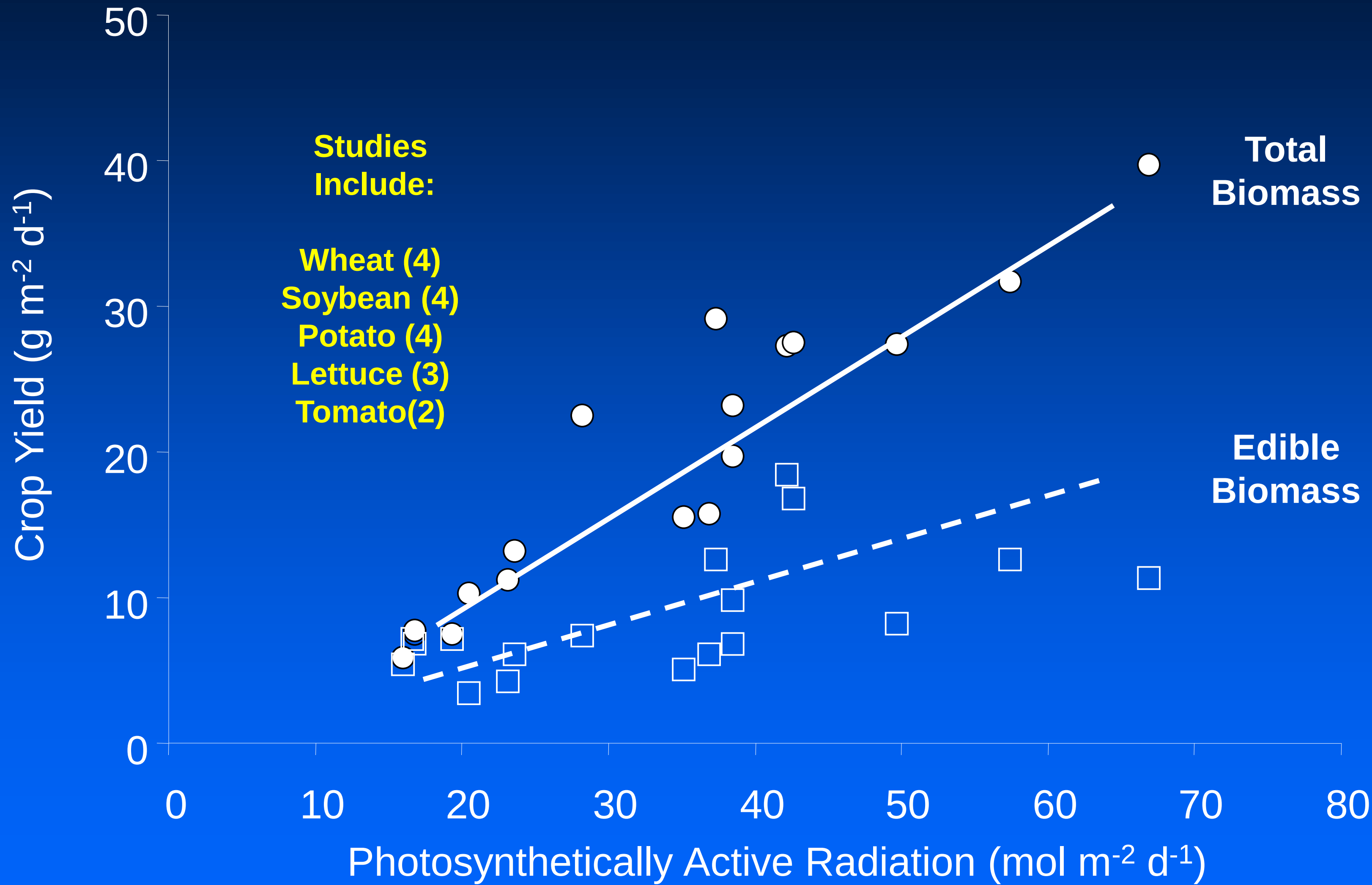
Potato
(Solanum tuberosum)

Automation Technologies for CEA



ALSARM Robot in NASA
Biomass Production Chamber

Effect of Light on Crop Yield



Wheeler et al. 1996. Adv. Space Res .

Electrical Power for BPC

- 96 400-W HPS lamps with dimming ballasts
- Two 30 kW blowers (400 m^3 min^{-1})
- Two 15-ton (52 kW) chillers for cooling
- 100 kW water heater for air re-heat

→ Not designed for energy efficiency!!

The Importance of Lighting

--Electric Lamp Options

Lamp Type	*Conversion* Efficiency*	*Lamp Life* (hrs)*	*Spectrum*
• Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000-20,000	Broad
• Metal Halide	25%	20,000	Broad
• High Pressure Sodium	30%	25,000	Intermd.
• Low Pressure Sodium	35%	25,000	Narrow
• Microwave Sulfur	35-40%+	?	Broad
• LEDs (red and blue)****	>40%	100,000 ?	Narrow

* *Approximate values.*

** *Tungsten halogen lamps have broader spectrum.*

*** *For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.*

**** *State-of-Art Blue and Red LEDs most efficient.*

LED Studies

Red...photosynthesis
Blue...photomorphogenesis
Green...human vision

Some NASA Related References:

Bula et al. 1991. HortSci 26:203-205.

Barta et al. 1992. Adv. Space Res. 12(5):141-149.

Tennessen et al. 1994. Photosyn. Res. 39:85-92.

Goins et al. 1997. J. Exp. Botany 48:1407-1413.

Kim et al. 2004. Ann. Bot. 94:691-697.

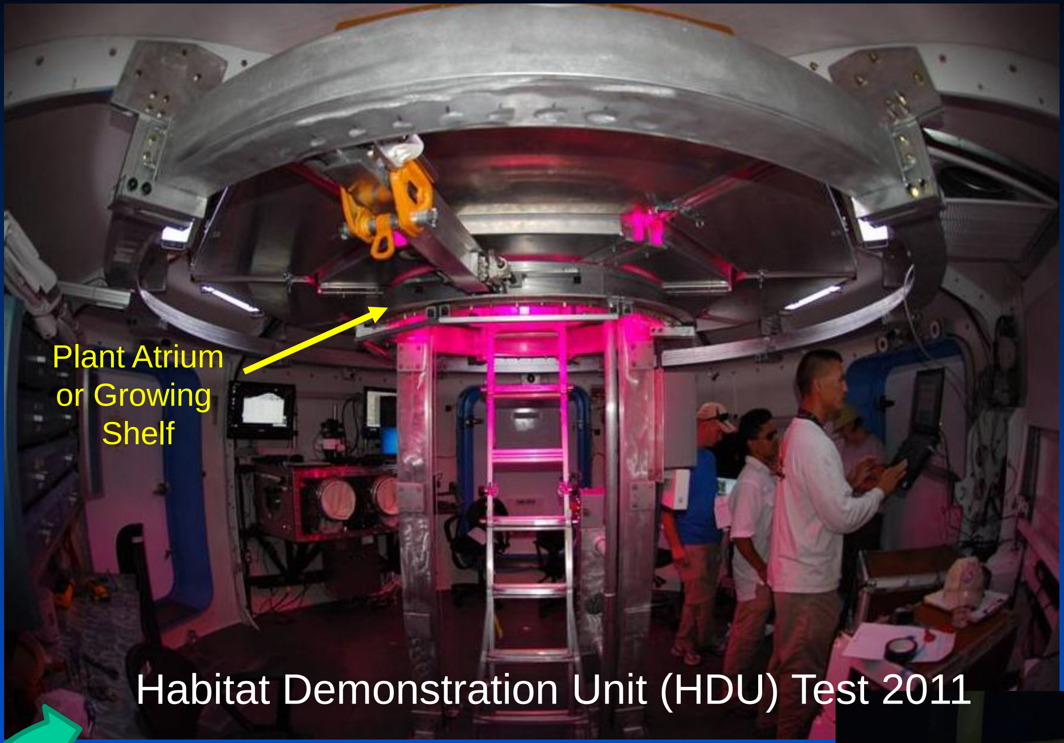
Solar Collector / Fiber Optics For Plant Lighting

2 m^2 of collectors on solar tracking drive (SLSL Bldg, NASA KSC)

Up to 400 W light delivered to chamber (40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

Nakamura et al. 2010. Habitation

Human Habitats and Crops for Supplemental Food

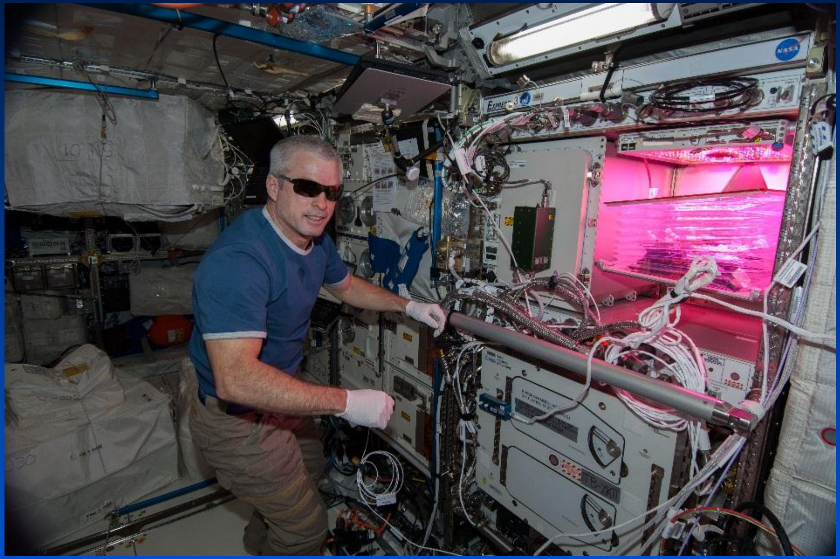


Habitat Demonstration Unit (HDU) Test 2011

NASA's HDU at Desert Test Site


HDU Test 2012

Plant Growth on the International Space Station—VEGGIE Plant Chamber.



Some Lessons Learned from NASA CEA / Vertical Ag work

- Over half of maintenance / upkeep time dedicated to nutrient system management
  - If condensate water is retrieved, pay attention to elemental content
- Extensive work for optimizing hydroponic solution replenishment recipes
  - We made no attempts to reduce nitrate in tissue
- Consider ability to reach all sections of the growing area; it was not easy for use to inspect the back of our trays; consider shelf-to-shelf height
- Initially we sanitized hydroponic hardware following crops, but later abandoned in favor of thorough cleaning
- Consider innovative means for improving energy efficiency, e.g., if possible use heat from lamps and power supplies for air “re-heat”
- Worker safety—consider sunglasses for working around bright red and blue LEDs

Agriculture in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth


KSC Advanced Life Support Team, Hangar L, KSC 1994